Forest Ecology and Management 257 (2009) 1231–1236

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Aerially applied methylcyclohexenone-releasing flakes protect *Pseudotsuga menziesii* stands from attack by *Dendroctonus pseudotsugae*

N.E. Gillette [a,*], C.J. Mehmel [b], J.N. Webster [c], S.R. Mori [a], N. Erbilgin [d,e], D.L. Wood [e], J.D. Stein [f]

[a] USDA Forest Service PSW Research Station, Berkeley, CA 94701, United States
[b] USDA Forest Service, Forest Health Protection, Wenatchee, WA 98801, United States
[c] Total Forestry, Anderson, CA 96007, United States
[d] Department of Renewable Resources, University of Alberta, Edmonton, AB T6G 2E3, Canada
[e] Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720, United States
[f] Retired from USDA Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV 26505, United States

ARTICLE INFO

Article history:
Received 14 May 2008
Received in revised form 31 October 2008
Accepted 8 November 2008

Keywords:
Pheromones
Bark beetles
Scolytidae
Semiochemicals
Douglas-fir beetle
Scolytinae
Curculionidae

ABSTRACT

We tested methylcyclohexenone (MCH), an anti-aggregation pheromone for the Douglas-fir beetle (*Dendroctonus pseudotsugae*), for protection of Douglas-fir (*Pseudotsuga menziesii*) stands by applying MCH-releasing polymer flakes by helicopter twice during summer 2006 to five 4.05-ha plots in the State of Washington, USA. Five similar plots served as untreated controls. We assessed *D. pseudotsugae* flight into study plots using baited pheromone traps, and tallied *D. pseudotsugae* attack rates on all *P. menziesii* trees in 2005 and 2006. We also measured stand basal area and incorporated that as an explanatory variable in the analysis. Significantly fewer *D. pseudotsugae* were trapped in treated plots than in control plots, and significantly fewer *P. menziesii* trees were attacked in treated plots than in control plots. The attack rate in untreated stands was nearly 10 times that of treated plots, and stands with higher basal area were significantly more likely to be attacked by *D. pseudotsugae* than were stands of lower basal area. Attack rates in 2006 and 2005 were significantly correlated, regardless of treatment.

Published by Elsevier B.V.

1. Introduction

Dendroctonus pseudotsugae Hopkins, the Douglas-fir beetle, is the most damaging beetle pest of Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, throughout its range in western North America (Furniss and Carolin, 1977; Sanchez Salas et al., 2003). Outbreaks are normally sporadic and often follow wind throw or wildfires, but losses can be extensive (Dodds et al., 2004, 2006). More recently, drought has been implicated as a risk factor for *D. pseudotsugae* damage (Powers et al., 1999) and climate predictions suggest that localized droughts are likely to increase (Breshears et al., 2005). Heavily stocked or old growth stands are particularly at risk (Negron, 1998; Bulaon, 2003; Dodds et al., 2004; Cunningham et al., 2005; Hood and Bentz, 2007), and such stands serve as crucial habitat for the Northern Spotted Owl, *Strix occidentalis* (Xantus de Vesey), and the endangered Marbled Murrelet, *Brachyramphus marmoratus* (Gmelin). The need to conserve habitat for such protected species requires reduced harvests to maintain old growth stand structure (Noon and Blakesley, 2006; Raphael, 2006), resulting in greater risk of *D. pseudotsugae* outbreaks. In addition, managers of forested public lands have recently begun to fell *P. menziesii* trees to provide down woody debris for wildlife, because sufficient habitat is not created naturally in intensively managed forests (Ross et al., 2006). This practice, however, exacerbates outbreaks of *D. pseudotsugae* by providing breeding material for beetle populations that then spread the following year to standing trees (Furniss and Carolin, 1977; Ross et al., 2006). Forest managers have therefore sought methods to manage this pest, especially following such stand disturbances as wildfire and storms resulting in extensive wind throw, which exacerbate the situation by increasing stand susceptibility and providing breeding material for rapid beetle population buildup. Many of the stands that require protection from *D. pseudotsugae* are steep and/or remote, presenting difficulties for access using ground-level tree protection treatments. Furthermore, beetle flight begins when roads in many areas are impassable, making the possibility of an aerially applied treatment highly desirable.

Several management techniques to control *D. pseudotsugae* have been tested, including silvicultural treatments (Ross et al., 2006), insecticide applications (Furniss, 1962; Ibaraki and Sahota,

* Corresponding author at: USDA Forest Service, PSW Research Station, P.O. Box 245, Berkeley, CA 94701, United States. Tel.: +1 510 559 6474; fax: +1 510 559 6440.
E-mail address: ngillette@fs.fed.us (N.E. Gillette).

0378-1127/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.foreco.2008.11.037

1976), peeling of beetle-infested bark (Shore et al., 2005), and pheromone-based strategies including aggregation pheromones deployed in trap-out or trap-tree approaches (Ross and Daterman, 1995, 1997, 1998; Dodds et al., 2000; Laidlaw et al., 2003) and antiaggregants to interrupt host-finding (Furniss et al., 1972, 1974, 1977, 1982; McGregor et al., 1984; Ross and Daterman, 1994, 1995; Ross et al., 1996; Dodds et al., 2000). Reducing stand basal area may be the single most effective treatment (Dodds et al., 2004, 2006), but forest management objectives, particularly on public lands, often require preservation of large old-growth trees for wildlife habitat (Noon and Blakesley, 2006). Insecticide applications are likewise frequently ruled out because of adverse effects on nontarget organisms (e.g. Loch, 2005; Kreutzweiser et al., 2008; Kwon, 2008). Treatments such as trap-out, trap trees, and bark peeling (Laidlaw et al., 2003) are promising for small, high-value stands, but are labor-intensive and are thus unlikely to be used over large areas. They are also most appropriate for stands that are either spatially or ecologically isolated (i.e. surrounded by immature or non-host forest).

The anti-aggregation pheromone for *D. pseudotsugae*, 3-methyl-2-cyclohexen-1-one (MCH), has been tested for decades for area-wide control in various release formulations (Furniss et al., 1972, 1974, 1977, 1982; McGregor et al., 1984; Ross and Daterman, 1994, 1995; Ross et al., 1996; Dodds et al., 2000). MCH is produced *in vivo* by some animals and is found in a variety of foods; it was approved by the Food and Drug Administration as a food additive (Syracuse Environmental Research, Inc., 1998) and is currently registered by the United States Environmental Protection Agency for use in forestry. Various release devices have been tested, including granular MCH-releasing formulations, 3 mm polymer beads coated with MCH, and MCH-containing bubble-capsules that are stapled to individual trees or dispersed throughout wind thrown trees. One type of polymer bead was shown to release MCH too quickly for operational use (Holsten et al., 2002), and the granular formulation was promising but was not implemented on a broad scale for logistical reasons (M. Furniss, personal communication). Bubble capsules are quite effective but are limited in their application to relatively small, accessible stands. A new "puffer" device that periodically emits MCH has shown promise for control of *Dendroctonus rufipennis* (Kirby) (Holsten et al., 2006), but this device may not be adaptable for area-wide treatments because of its bulk, weight, and high cost.

We chose to assess efficacy of MCH-impregnated laminated plastic flakes, an existing pheromone release device that has been used for decades in the USDA Forest Service's "Slow-the-Spread" program to control the invasive Gypsy Moth (Sharov et al., 2002). We selected this application system because of its favorable release patterns (Gillette et al., 2006), its favorable regulatory characteristics (it was already registered for pheromones of the Gypsy Moth and orchard pests) and because of its ease of application with existing aircraft adaptations (i.e. pods and hoppers for use with fixed-wing aircraft and helicopters). Although the current formulation does not biodegrade quickly, a new biodegradable formulation is now available and will be tested in the near future.

2. Materials and methods

2.1. Study location

We installed the study in early 2006 near Lake Chelan in northern Washington State, USA. The site was located in Chelan County, Washington, on the Chelan Ranger District, Okanogan-Wenatchee National Forest, T28N R20E, Willamette Meridian, eight air miles northwest of the town of Manson, WA. The area was part of the Pot Peak Fire Complex, which began on June 26, 2004 and burned a total of 47,000 acres. Numerous Douglas-fir beetle attacks on scorched Douglas-firs were noted in 2005, indicating a potential outbreak. We selected ten 4.05-ha plots, at least 400 m apart, with apparently similar basal areas and existing rates of *D. pseudotsugae* infestation (Table 1). We did not have sufficient resources to assess these variables both before and after the treatments; since we were able to quantify both of them after the pheromone application, we chose to do so then, and to incorporate them as covariates in the analysis so their effects would be accounted for and any potential differences would not affect our ability to assess a treatment difference. We randomly assigned treatment to half of the plots, reserving the remaining half as untreated controls. A core plot of 2.03 ha was established in the center of each of the ten plots so that treatment effects (beetle flight and rate of attack on trees) could be measured while avoiding edge effects.

2.2. Pheromone formulation

MCH-releasing flakes (Hercon Environmental Emigsville, PA, USA) were formulated to contain 15% MCH in a central layer of plastisol bounded by two layers of polymer laminate. This laminated formulation, which is prepared in sheets and then cut into small square "flakes," releases the active ingredient (AI) only at the perimeter (not from the upper or lower surfaces) of each 6.4 mm $\times$ 6.4 mm square flake. Each flake thus represents a small reservoir of MCH with limited pheromone-releasing surface-to-volume ratio; these attributes result in sustained release of the pheromone over time. For example, release rates calculated from laboratory tests indicate release of 0.31 mg/AI/cm^2 of flakes/day between day 7 and day 14 following application (personal communication, Norris Starner, Hercon Environmental, Emigsville, PA). MCH is a more compact and lower-molecular weight molecule than many beetle pheromones, however, with only seven carbons and a single branch, as compared to verbenone and ipsdienol, which have ten carbons and are multiply branched (www.pherobase.com). It may thus elute more rapidly than some other beetle pheromones, so we scheduled a second application in the event that the flakes might become depleted of pheromone before the end of beetle flight.

2.3. Application rate and timing

The first application was made on 5 May 2006 and the second on 29 June 2006 at the rates of 468 g AI/ha (1.3 kg of flakes/ha) and

Table 1
Stand structure characteristics and pre- and post-treatment attack rates in treated and control plots, Chelan, WA, 2006.

Treatment	Mean (SE) total basal area (m^2/ha)[a]	Mean (SE) *P. menziesii* basal area (m^2/ha)[a]	Mean (SE) number of stems/ha[a]	Mean (SE) number of *P. menziesii* stems/ha[a]	Mean (SE) number of *P. menziesii*/ha attackedin 2005[a]	Mean (SE) number of *P. menziesii*/ha attacked in 2006[a]	Mean (SE) DBH, all trees	Mean (SE) DBH, *P. menziesii* trees
Control	29 (2) a	26 (2) a	276 (37) a	253 (26) a	0.6 (0.4) a	6.23 (1.9) a	34.8 (2.6)a	34.7 (2.5) a
Treated	21 (4) a	17 (4) a	201 (44) a	175 (47) a	0.1 (0.1) a	0.30 (0.1) b	33.9 (0.7)a	33.7 (1.4) a
Control/treated	1.378	1.513	1.383	1.437	6.0	21	1.03	1.03
P-value	0.12	0.10	0.21	0.18	0.10	$<$0.0001	0.75	0.72

[a] Means (SE = standard error); means followed by the same letter are not significantly different at α = 0.05.

370 g AI/ha (1.0 kg of flakes/ha), respectively. We applied a lower rate at the second application because we expected lower beetle populations later in the season. Application was made using a Bell 47-G3B2A turbine helicopter equipped with two side pods, each equipped with augers feeding a hydraulic spinner to achieve even distribution of flakes. The airspeed during application was 72.5 km/h. Evenness and precision of application were assessed by placing, at random, four pieces of 1 m $\times$ 1 m cardboard per plot, each sprayed with a tacky substance to catch dispersing flakes; flakes were counted immediately following application.

2.4. Beetle flight and stand measurements

Immediately following treatment, four Intercept panel traps (Advanced Pheromone Technologies, Marylhurst, OR, USA) were placed in each 2.03 ha core plot, with one trap in each of the cardinal directions (i.e. the NW, NE, SW and SE corners). Traps were suspended at a height of 2 m near the corners of the core plots, but as far away as possible from host trees. Traps were baited with the aggregation pheromone of *D. pseudotsugae*, seudenol (3-methyl-2-cyclohexen-1-ol) and frontalin (Phero Tech International), and lures were refreshed twice during the post-treatment assessment period, on 19 June and 17 July 2006. Two insecticide-releasing strips (Hercon Environmental) were placed in each trap collection cup to avoid predation. We collected the beetles caught in these traps once a week for 16 weeks following application. Beetles were identified and counted, and voucher specimens were sent to the Essig Museum of Entomology, University of California, Berkeley, CA, USA. Stand conditions and pre- and post-treatment attack rates were assessed during 5–8 September 2006 by conducting a 100% timber cruise of each core plot at the end of beetle flight in 2006. As explained earlier, we had insufficient resources to conduct this cruise twice, but since we were able to assess both pre- and post-treatment conditions during a single post-treatment cruise, this did not present an obstacle in conducting the study. Pre-treatment variables assessed during this cruise were used as covariates, so any differences in pre-existing conditions were accounted for in the analysis. The cruise consisted of documentation of all trees over 20 cm DBH (diameter at breast height) by species, DBH, and 2005/2006 attack status of each tree. Trees smaller than 20 cm DBH are not suitable hosts for *D. pseudotsugae* and do not contribute meaningfully to plot basal area, which is a surrogate for tree stress, so these trees were not included. Beetle attacks were identified by the presence of entrance holes and boring dust (Furniss and Carolin, 1977).

2.5. Statistical analysis

Differences between stand attributes were assessed using the *t*-test from the SAS Mixed procedure (SAS Institute, 1997). The number of attacked trees per plot in 2006 (post-treatment) was analyzed with a Poisson Regression Model for over-dispersed Poisson-distributed responses to address the discrete nature of the response (counts) and the variability associated with plot (McCulloch and Searle, 2001). The explanatory variables were treatment (control and treated), number of attacked trees in 2005, and total plot basal area. The logarithm of the number of trees in each plot was used as an offset to estimate the proportion of attacked trees per acre. The Poisson Regression Model belongs to the family of Generalized Linear Models (McCulloch and Searle, 2001). The regression model:

$$\text{Expected}\,[\text{att2006}_{i,j}|\varepsilon_j] = e^{\mathrm{T}_i + b\times \text{att 2005}_j + c\times \text{plot BA}_j + \log(\text{trees in plot}_j) + \varepsilon_j},$$

where attacked $2006_{i,j}$ is the number of attacked trees in 2006 in plot *j*; T_i is the treatment effect (*i* = 1 control, *i* = 2 treated); *b* and *c* are the regression coefficients for number of trees attacked in 2005 and plot basal area in plot *j*, respectively; log(# trees in plot *j*) is the logarithm of the number of trees in plot *j*; ε is the over-dispersion error due to plot variability, and "|" means "conditioned to."

The proportion of attacked trees (attack rate) in 2006 can be obtained from the model above, since this model is equivalent to:

$$\frac{\text{Expected}\,[\text{att2006}_{i,j}|\varepsilon_j]}{\text{trees in plot } j} = e^{\mathrm{T}_i + b\times \text{att 2005}_j + c\times \text{plot BA}_j + \varepsilon_j}$$

The parameters were estimated using the Maximum Likelihood Estimation technique with the SAS (v. 9.1.3) GENMOD procedure. The experiment-wise error rate was 0.05.

The number of beetles trapped in 2006 in each plot was also analyzed with a Poisson Regression Model for over-dispersed Poisson-distributed responses to address both the discrete response and the variability associated with multiple traps in each plot through time (sampling every 7 days) (McCulloch and Searle, 2001). Explanatory variables were treatment (control vs. treated) and sampling period (16 weeks). Because the number of days between samples was not always exactly seven, the logarithm of the number of days was used as an offset. The regression model:

$$\text{Expected}\,[\text{beetle count}_{i,j,c,p}|\varepsilon_{c,p}] = e^{\mathrm{T}_i + \text{week}_j + \log(\text{days}_j) + \varepsilon_{c,p}},$$

where beetle count is the number of trapped beetles; T_i is the treatment effect (*i* = 1 control, *i* = 2 treated); week_j is the time effect (*j* = 1, 2, ..., 16) as a fixed block effect; log(# days) is the logarithm of the number of days between samples; $\varepsilon_{c,p}$ is the random effect (over-dispersion error) accounting for corner trap nested in plot variability, and "|" means "conditioned to." The parameters were estimated with SAS GENMOD procedures as above.

3. Results

Stand structure and pre-existing beetle attack rates did not differ significantly between treated and control plots (Table 1). Mean basal area for all conifer species combined was 21 m^2/ha in treated plots vs. 29 m^2/ha in control plots, and the values for mean stems per acre were 201 and 276 for treated vs. control plots. Mean basal areas for *P. menziesii*, the only host tree species for *D. pseudotsugae*, were 17 m^2/ha and 26 m^2/ha for treated vs. control plots, and mean stems per hectare were 175 and 253, respectively. On the other hand, the pre-existing beetle populations were higher in control plots than treated plots, but populations were nevertheless rather low in both. The only significant difference between treated and control plots was the post-treatment mean attack rate, which was 6.23 trees/ha for controls, and 0.30 trees/ha for treated plots ($P < 0.0001$) (Table 1).

The attack ratio (control:treated) in 2006 was 9.77:1 ($P = 0.0002$) (Table 2, Fig. 2). Plots with higher numbers of attacked trees in 2005 had significantly higher levels of attack in 2006, because the coefficient for pre-existing attack rate was positive and significant (Table 2) ($P = 0.031$). Plots with higher basal areas likewise had significantly higher levels of attack, independent of treatment, because the coefficient for basal area was also positive and significant (Table 2) ($P = 0.005$).

Table 2
Estimates of the back-transformed regression coefficients for basal area and previous year (2005) attack rate, Chelan, WA, 2006.

Parameter	Estimate	Lower 95% CI	Upper 95% CI	*P*-value
2005 attack coefficient	0.137	0.0124	0.261	0.031
Plot basal area coefficient	0.004	0.0013	0.0075	0.005
Ratio, control/treated	9.77	2.97	32.11	0.0002

We caught 143,344 beetles in the entire sampling period. Traps in control plots caught significantly more beetles than traps in treated plots (more than eight times as many: 95% confidence interval: [5,12]; $P < 0.0001$), with peak beetle catches approaching 25,000 per week in control plots and 3000 per week in treated plots (Fig. 2). There were two main peaks in numbers of beetles trapped, one at 2 weeks following treatment (19 May) and one at 8 weeks following treatment (23 June) (Fig. 2). Each of these peaks occurred shortly after the installation of fresh lures (on 5 May and 19 June), and the effect was seen in both treated and control plots. There was no similar peak following the final refreshing of lures on 17 July. Numbers of beetles were very low in treated plots throughout the sampling period.

The rate of attack in treated plots was reduced to nearly zero (Fig. 2), even for higher stand basal areas and higher pre-existing beetle populations where it is more difficult to achieve control. Plots with higher basal areas and higher pre-existing beetle populations, as noted above, had higher attack rates in 2006 than plots with lower basal areas and lower pre-existing beetle attack rates.

4. Discussion

We found a significant, positive treatment effect in terms of tree protection, with fewer attacked trees after treatment in treated plots than in control plots (63 vs. 3 trees); this effect was independent of basal area and pre-existing beetle populations, since those factors were included as covariates and were thus accounted for in the analysis. The reduction in attack rate achieved by reducing beetle attraction into treated stands (Figs. 1 and 2) was considerable, with attack rates in treated stands close to zero (Fig. 2A–C). These results agree with previous studies, which showed that a variety of MCH formulations were effective for managing *D. pseudotsugae* damage (Furniss et al., 1982; McGregor et al., 1984; Ross et al., 1996). The success of MCH treatments using other MCH dispensers would suggest that MCH-releasing flakes may be equally effective at lower application rates than we used. For example, (Ross et al., 1996) found no differences in efficacy with a range of six release rates using bubblecap dispensers; even the lowest rate gave significant protection, and they speculated that equal or greater efficacy might be achieved with even lower

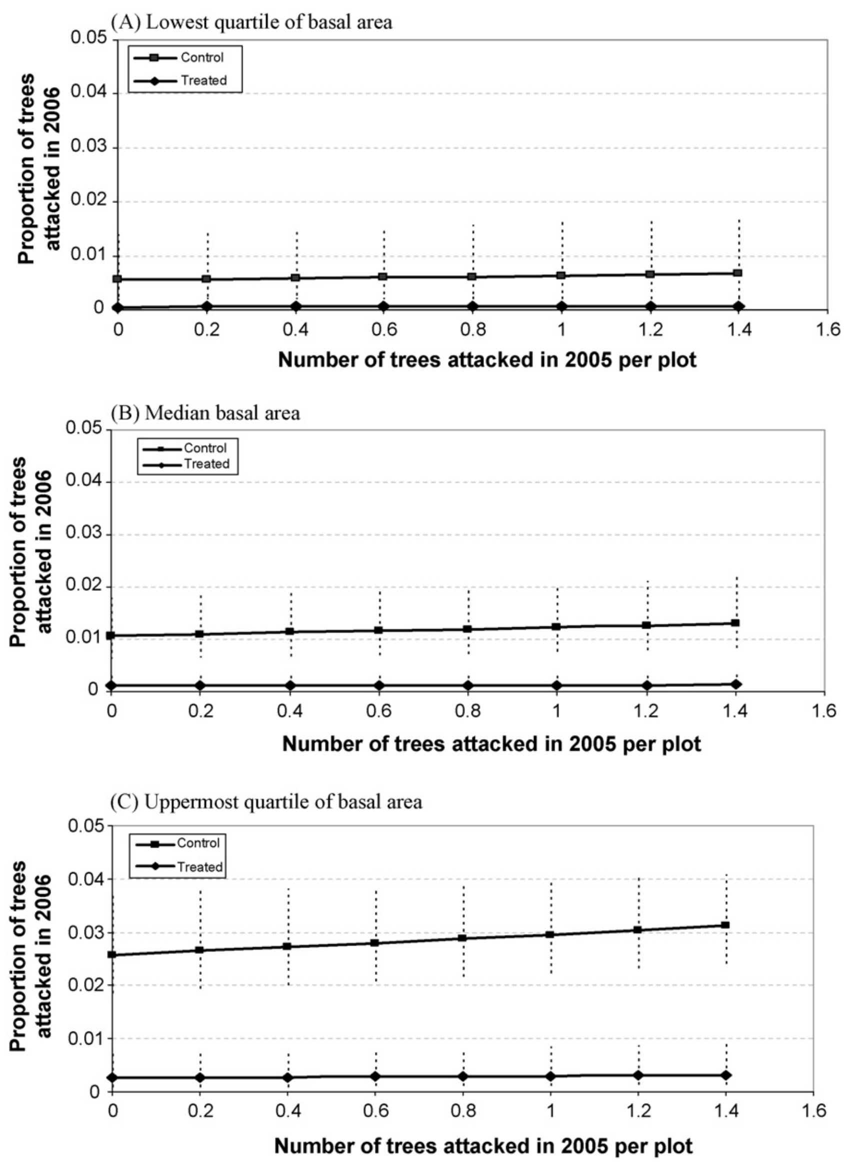

Fig. 1. Attack rate in 2006 (with 95% CL) as a function of pre-existing *D. pseudotsugae* populations for (A) lower quartile, (B) median quartile, and (C) upper quartile of plot basal areas.

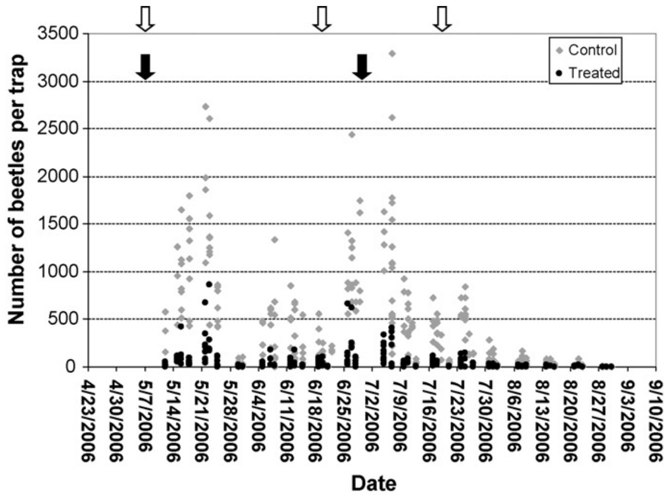

Fig. 2. Time sequence of beetle response to traps, pheromone applications, and lure renewals in Chelan, Washington, 2006. Black arrows indicate timing of pheromone applications and white arrows indicate placement of fresh lures in traps; gray diamonds = controls; black circles = MCH-treated plots.

rates. Further testing should be conducted to assess whether equivalent efficacy might be achieved with a lower application rate of flakes. More testing is also warranted to assess efficacy of flakes at higher beetle populations.

Stand basal area and pre-existing beetle populations proved to be significant covariates (Table 2), confirming findings in previous studies of *D. pseudotsugae* outbreak dynamics (Negron, 1998; Dodds et al., 2006) which found higher *D. pseudotsugae* attack rates in stands with higher pre-existing beetle populations and higher basal areas. While these results indicate that maintaining lower basal area could be an effective means to manage *D. pseudotsugae*, forest management objectives often limit the ability of forest managers to use such silvicultural methods to avoid pest problems.

The time trends in response of beetles to baited traps (Fig. 2) suggest that, under these conditions, the second application of MCH flakes may not have been necessary in order to achieve control of *D. pseudotsugae*. Beetle trap catch in control plots began to increase sharply on the 25 June collection but increased only slightly in treated plots, suggesting that the flakes were still releasing enough MCH to interrupt beetle flight into treated plots despite the presence of fresh lures. The high trap catches in the 25 June collection from control plots were probably more a result of the deployment of fresh lures than of a surge in beetle populations. It has been reported that the *D. pseudotsugae* aggregation pheromone is an extremely strong cue, drawing beetles from more than 200 m to baited traps (Dodds and Ross, 2002) so newly deployed lures can be misleading inasmuch as they attract large numbers of beetles for the first week or two following deployment. In addition, Laidlaw et al. (2003) found that beetle catch in baited traps continued at midseason after beetles had ceased attacking trees, so beetle trap catch at that point in the season may not be a good indicator of midseason attack rate. In our study, beetle trap catch in control plots began declining by the time of the 9 July collection and remained low thereafter, indicating that beetle flight was certainly subsiding by that time. Since it is not practical to assess seasonal trends in beetle population without the use of these aggregation pheromones, it is difficult to avoid this potentially confounding factor in the design of efficacy studies. We conclude, however, that beetle flight was probably beginning to subside at the time of the second application, so for operational purposes a single application might suffice. This question requires further testing, for example a comparison of single vs. double applications.

This study assessed use of an anti-aggregation pheromone to protect *P. menziesii* stands, but even better efficacy may be achieved using this technique in combination with aggregation pheromones deployed in a trap-out strategy, i.e. with baited traps surrounding the area treated with anti-aggregants. Indeed, Ross and Daterman (1994) found that treating with MCH-releasing bubblecaps concentrated *D. pseudotsugae* attack onto trees within a limited area outside the treated stand, so it would be wise to test the combined approach in the future.

Further testing is recommended to determine the lowest application rate and confirm efficacy for higher beetle populations, but trends in climate change (Breshears et al., 2005) and forest stand conditions (Hessburg et al., 2000) suggest a continuing need for this type of area-wide treatment for bark beetle management. Our study was conducted under low beetle populations, but with predicted climate change we expect populations to increase. While we recognize the value of reducing basal area to minimize stand susceptibility to *D. pseudotsugae*, thinning of stands is time-consuming. Pheromones, which can reach the target pest more effectively than contact insecticides, often have the further advantage of not disrupting natural enemy complexes (Ross and Daterman, 1995). MCH bubblecaps or other hand-applied methods will remain important for campgrounds, parks, and other accessible sites. MCH aerial treatments, on the other hand, may prove useful for rapid response in inaccessible areas and larger landscapes following wildfire and windstorms when stands are temporarily vulnerable to attack and there is not time to conduct thinning to reduce stand susceptibility. Such treatments could also be conducted to prevent *D. pseudotsugae* outbreaks following the creation of artificial down woody debris. They will also be useful for protecting old-growth stands that must be managed at high basal areas in order to provide habitat for wildlife. Ground applications of flakes made with broadcast spreaders and/or paint-ball applicators can also be used in campgrounds, administrative areas, and ski resorts, where aerial applications may not be acceptable. The efficacy of MCH-releasing flakes for *D. pseudotsugae* control offers the possibility of a truly rapid, area-wide response to bark beetle outbreaks.

Acknowledgements

This project was funded by a grant from the USDA Forest Service, Forest Health Technology Enterprise Team (Morgantown, WV). We thank James Heath and Priscilla McLean, Hercon Environmental, Emigsville, PA, for providing MCH-releasing flakes to our specifications for testing; John Mateski, Western Helicopter, Newberg, Oregon, for providing a meticulous application of flakes. We thank Kevin Dodds (USDA Forest Service, Durham, New Hampshire) for a review that greatly improved the manuscript. We also gratefully acknowledge Mallory Lenz, wildlife biologist on the Chelan Ranger District, for invaluable assistance with logistics and the NEPA process, Roy Maggelsen for GIS assistance and for his incredible stamina and agility in the field, and our student assistant Kirsten Addis, for patient collection, identification, and counting of beetles all summer long.

References

Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Balice, R.G., Romme, W.H., Kastens, J.H., Floyd, M.L., Belnap, J., Anderson, J.J., Myers, O.B., Meyer, C.W., 2005. Regional vegetation die-off in response to global-change-type drought. Proc. Natl. Acad. Sci. U.S.A. 102, 15.144–15.148.

Bulaon, B., 2003. Douglas-fir Beetle Surveys of the Fires of 2000 in the Northern Region, Forest Health Protection, Spring 2003. In: USDA Forest Service, Forest Health Report, Northern Region. Missoula, MT 03-2, 10.

Cunningham, C.A., Jenkins, M.J., Roberts, D.W., 2005. Attack and brood production by the Douglas-fir beetle (Coleoptera: Scolytidae) in Douglas-fir, *Pseudotsuga*

menziesii var. *glauca* (Pinaceae), following a wildfire. West. North Am. Nat. 65, 70–79.
Dodds, K.J., Ross, D.W., 2002. Sampling range and range of attraction of *Dendroctonus pseudotsugae* pheromone-baited traps. Can. Entomol. 134, 343–355.
Dodds, K.J., Ross, D.W., Daterman, G.E., 2000. A comparison of traps and trap trees for capturing Douglas-fir beetle, *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae). J. Entomol. Soc. B.C. 97, 33–38.
Dodds, K.J., Ross, D.W., Randall, C.B., Daterman, G.E., 2004. Landscape level validation of a Douglas-fir beetle stand hazard-rating system using geographical information systems. West. J. Appl. For. 19, 77–81.
Dodds, K.J., Garman, S.L., Ross, D.W., 2006. Risk rating systems for the Douglas-fir beetle in the interior Western United States. West. J. Appl. For. 21, 173–177.
Furniss, M.M., 1962. Effectiveness of DDT for preventing infestation of green logs by the Douglas-fir beetle (*Dendroctonus pseudotsugae*). Res. Note Intermountain For. Range Exp. Station 96, 10.
Furniss, R.L., Carolin, V.M., 1977. Western Forest Insects. In: USDA Forest Service Miscellaneous Publication 273, USDA Forest Service, WA, DC.
Furniss, M.M., Kline, L.N., Schmidt, R.F., Rudinsky, J.A., 1972. Tests of three pheromones to induce or disrupt aggregation of Douglas-fir beetles on live trees. Ann. Entomol. Soc. Am. 65, 1227–1232.
Furniss, M.M., Daterman, G.E., Kline, L.N., McGregor, M.D., Trostle, G.C., Pettinger, L.F., Rudinsky, J.A., 1974. Effectiveness of the Douglas-fir beetle antiaggregative pheromone methylcyclohexenone at three concentrations and spacings around felled host trees. Can. Entomol. 106, 381–392.
Furniss, M.M., Young, J.W., McGregor, M.D., Livingston, R.L., Hamel, D.R., 1977. Effectiveness of controlled-release formulations of MCH for preventing Douglas-fir beetle (Coleoptera: Scolytidae) infestation in felled trees. Can. Entomol. 109, 1063–1069.
Furniss, M.M., Markin, G.P., Hager, V.J., 1982. Aerial Application of Douglas-fir Beetle Antiaggregative Pheromone: Equipment and Evaluation. USDA Forest Service General Technical Report INT-137, Ogden, UT, p. 9.
Gillette, N.E., Stein, J.D., Webster, J.N., Fiddler, G.O., Mori, S.R., Wood, D.L., 2006. Verbenone-releasing flakes protect individual *Pinus contorta* trees from attack by *Dendroctonus ponderosae* and *Dendroctonus valens* (Coleoptera: Curculionidae, Scolytinae). Agric. For. Entomol. 8, 243–251.
Hessburg, P.F., Smith, B.G., Slater, R.B., Ottman, R.D., Alvarado, E., 2000. Recent changes (1930–1990s) in spatial patterns of interior northwest forests, USA. For. Ecol. Manage. 136, 53–83.
Holsten, E.H., Webb, W., Shea, P.J., Werner, R.A., 2002. Release Rates of Methylcyclohexenone and Verbenone from Bubblecap and Bead Releasers Under Field Conditions Suitable for the Management of Bark Beetles in California, Oregon, and Alaska. In: USDA Forest Service Research Paper PNW Research Station, PNW-RP-544, USDA Forest Service. Portland, OR p. 21.
Holsten, E.H., Shea, P.J., Borys, R.R., 2006. MCH released in a novel pheromone dispenser prevents spruce beetle, *Dendroctonus rufipennis* (Coleoptera: Scolytidae), attacks in south-central Alaska. J. Econ. Entomol. 96, 31–34.
Hood, S., Bentz, B., 2007. Predicting postfire Douglas-fir beetle attacks and tree mortality in the northern Rocky Mountains. Can. J. For. Res. 37, 1058–1069.
Ibaraki, A., Sahota, T.S., 1976. Effect of insect growth regulators on the survival of Douglas-fir beetle progeny. Bi-monthly Res. Notes 32, 3–5.
Kreutzweiser, D.P., Good, K.P., Chartrand, D.T., Scarr, T.A., Thompson, D.G., 2008. Nontarget effects on aquatic decomposer organisms of imidacloprid as a systemic insecticide to control emerald ash borer in riparian trees. Ecotox. Environ. Safety 68 (3), 315–325.
Kwon, T.S., 2008. Change of abundance of arthropods in pine forests caused by aerial insecticide sprays. Arch. Environ. Cont. Tox. 54 (1), 92–106.
Laidlaw, W.G., Prenzel, B.G., Reid, M.L., Fabris, S., Wieser, H., 2003. Comparison of the efficacy of pheromone-baited traps, pheromone-baited trees, and felled trees for the control of *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae). Environ. Entomol. 32, 477–483.
Loch, A.D., 2005. Mortality and recovery of eucalypt beetle pest and beneficial arthropod populations after commercial application of the insecticide alpha-cypermethrin. For. Ecol. Manage. 217 (2.3), 255–265.
McCulloch, C.E., Searle, S.R., 2001. Generalized, Linear, and Mixed Models. John Wiley & Sons, Inc., New York.
McGregor, M.D., Furniss, M.M., Oakes, R.D., Gibson, K.E., Meyer, H.E., 1984. MCH pheromone for preventing Douglas-fir beetle infestation in wind thrown trees. J. For. 82, 613–616.
Negron, J.F., 1998. Probability of infestation and extent of mortality associated with the Douglas-fir beetle in the Colorado Front Range. For. Ecol. Manage. 107, 71–85.
Noon, B.R., Blakesley, J.A., 2006. Conservation of the Northern Spotted Owl under the northwest forest plan. Conserv. Biol. 20, 288–296.
Powers, J.S., Sollins, P., Hamon, M.E., Jones, J.A., 1999. Plant-pest interactions in time and space: a Douglas-fir bark beetle outbreak as a case study. Landscape Ecol. 14, 105–120.
Raphael, M.G., 2006. Conservation of the Marbled Murrelet under the Northwest Forest Plan. Conserv. Biol. 20, 297–305.
Ross, D.W., Daterman, G.E., 1994. Reduction of Douglas-fir beetle infestation of high-risk stands by antiaggregation and aggregation pheromones. Can. J. For. Res. 24, 2184–2190.
Ross, D.W., Daterman, G.E., 1995. Efficacy of an antiaggregation pheromone for reducing Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins (Coleoptera: Scolytidae), infestation in high risk stands. Can. Entomol. 127, 805–811.
Ross, D.W., Daterman, G.E., 1997. Using pheromone-baited traps to control the amount and distribution of tree mortality during outbreaks of the Douglas-fir beetle. For. Sci. 43, 65–70.
Ross, D.W., Daterman, G.E., 1998. Pheromone-baited traps for *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae): influence of selected release rates and trap designs. J. Econ. Entomol. 91, 500–506.
Ross, D.W., Gibson, K.E., Thier, R.W., Munson, A.S., 1996. Optimal dose of an antiaggregation pheromone (3-methylcyclohex-2-en-1-one) for protecting live Douglas-fir from attack by *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae). J. Econ. Entomol. 89, 1204–1207.
Ross, D.W., Hostetler, B.B., Johansen, J., 2006. Douglas-fir beetle response to artificial creation of down wood in the Oregon Coast Range. West. J. Appl. For. 21, 117–122.
Sanchez Salas, J.A., Torres Espinosa, L.M., Cano Pineda, A., Martinez Burciaga, O.U., 2003. Damage and diversity of bark beetles on conifers in northeast Mexico. Ciencia Forestal en Mexico 28, 41–56.
Shore, T.L., Safranyik, L., Riel, W.G., Castonguay, J., 2005. Survival of the Douglas-fir beetle in peeled and unpeeled logs and in stumps. West. J. Appl. For. 20, 149–153.
Syracuse Environmental Research Associates, Inc., 1998. 3-Methylcyclohexen-1-one (MCH)—Human Health and Ecological Risk Assessment. Final Report. Animal and Plant Health Inspection Service (APHIS) Biotechnology, Biologics and Environmental Protection Environmental Analysis and Documentation, United States Department of Agriculture, Riverdale, MD.
SAS Institute, 1997. SAS/STAT Software: Changes and Enhancements Through Release 6.12. SAS Institute, Inc., Cary, NC.
Sharov, A.A., Leonard, D., Liebhold, A.M., Roberts, E.A., Dickerson, W., 2002. Slow the spread: a national program to contain the gypsy moth. J. For. 100, 30–35.